

# Canadian High-Energy Neutron Spectrometry and Mixed-Radiation Field Studies

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# Outline

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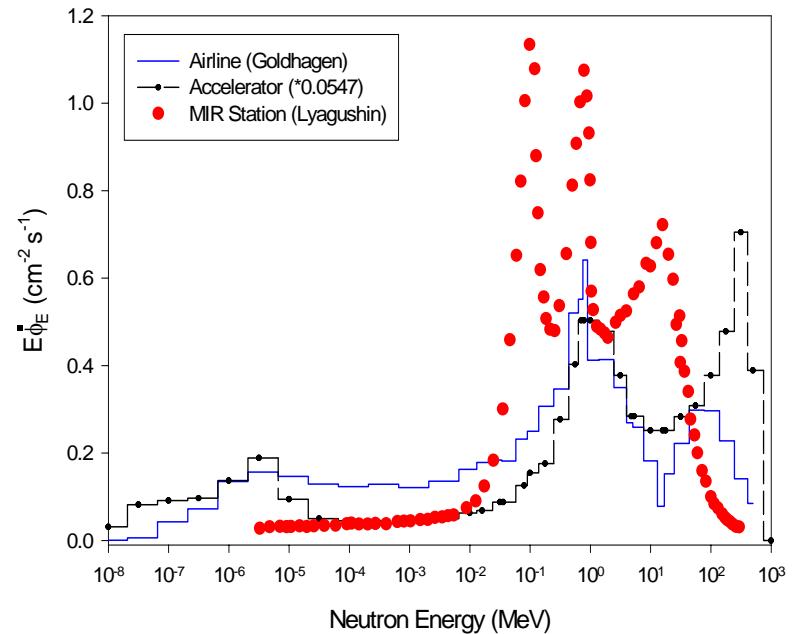
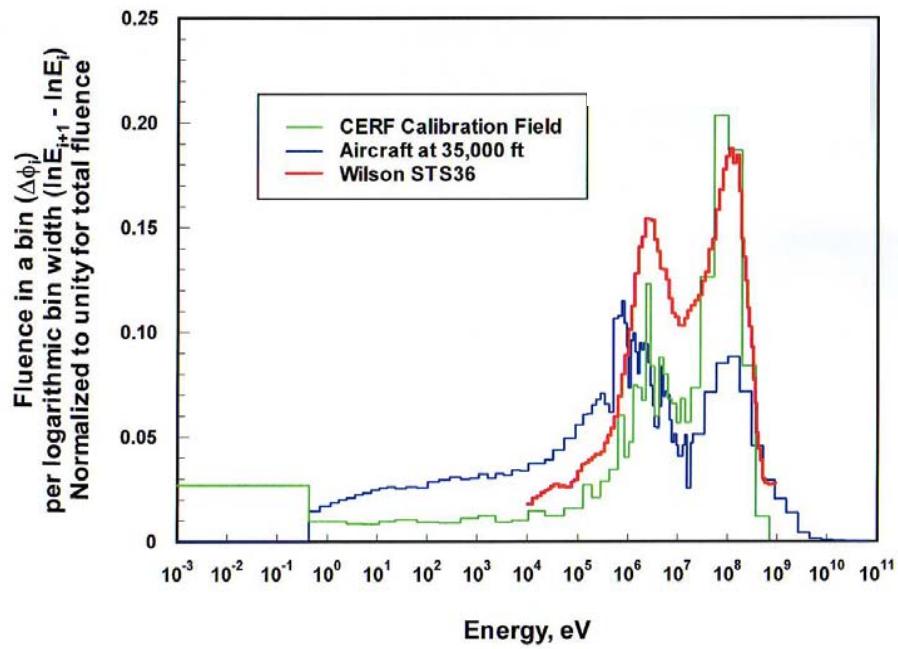
- Canadian High-Energy Neutron Spectrometry System (CHENSS)
- Mixed-Field Measurement
  - NFSE (bubble technology)
  - Tissue Equivalent Proportional Counter (TEPC)
  - Ionization chamber and SWENDI neutron remmeter
  - LIULIN (Si-based LET Spectrometer)
  - New technology: “DNA” dosimeter

# Neutron Dosimetry in Space

- Complex mixed charged particle and neutron environment exists in low Earth orbit (difficult to apply ground approaches)
  - Secondary neutrons (albedo neutrons from Earth's atmosphere and production from spacecraft shielding) contributes to 10-30% of total dose equivalent
    - TEPC gives reliable doses <20 MeV (response to higher energies?)
    - CR-39 passive dosimeters used to complement TEPC (and TLDs)
- Improve radiation dosimetry in space by accurately measuring the neutron fluence and neutron energy distribution
  - Measure/predict radiation dose to astronauts and optimize shielding scenarios



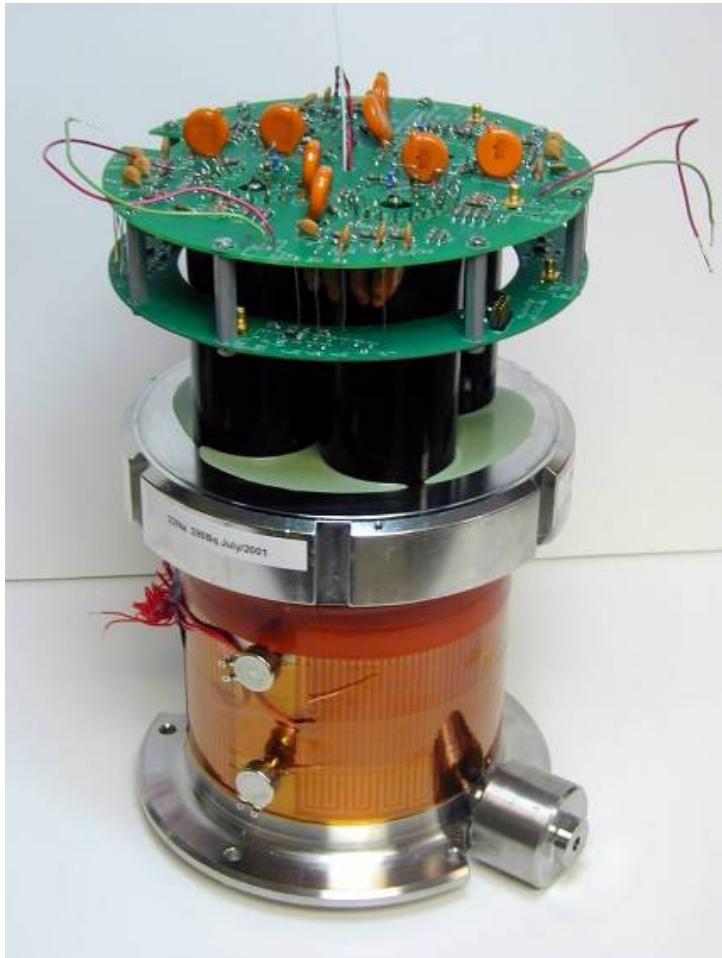
# Neutron Energy Distributions





# CHENSS:

## Canadian High-Energy Neutron Spectrometry System



- Three gain settings provide desired dynamic range (1 – 100 MeV scale)
- Internal  $^{22}\text{Na}$  (200 Bq)  $\gamma$ -ray source and two green LED's provide energy calibration and gain stability checks
- Amplitude and shape signals, hit patterns, scalers and diagnostics recorded on two hard drives
- 50 W power from alkaline batteries
- Designed for autonomous operation in NASA GAS can on space shuttle

**G. Jonkmans et. al.,  
Acta Astronautica 56, 975 (2005)**



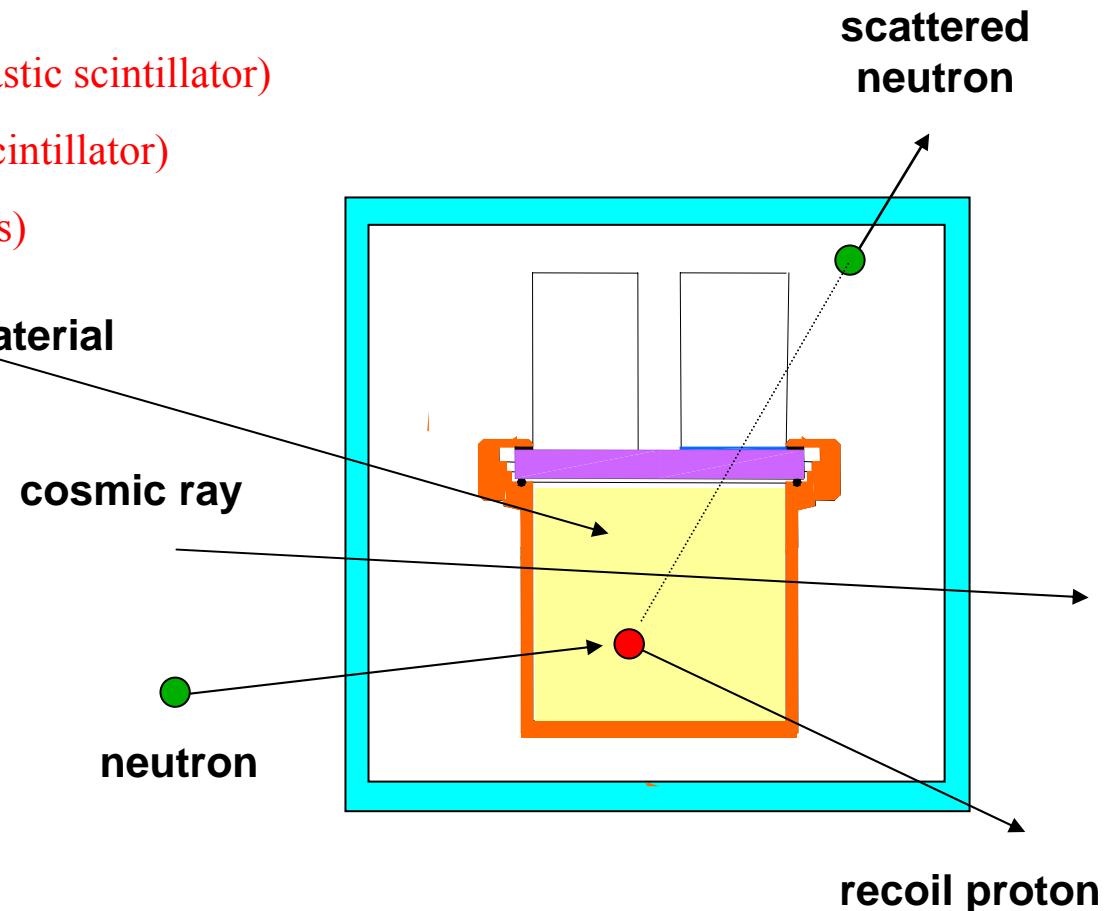
# CHENSS: Principle of Operation - Distinguishing Space Radiation

## Types of Space Radiation

- cosmic rays (vetoed by outer plastic scintillator)
- neutrons (detected by primary scintillator)
- electrons and  $\gamma$  rays (short pulses)

**hydrogenous scintillating material  
(xylene + naphthalene)**

good n- $\gamma$  discrimination  
isotropic response  
reliable cross-sections





# Constraints Imposed by Space

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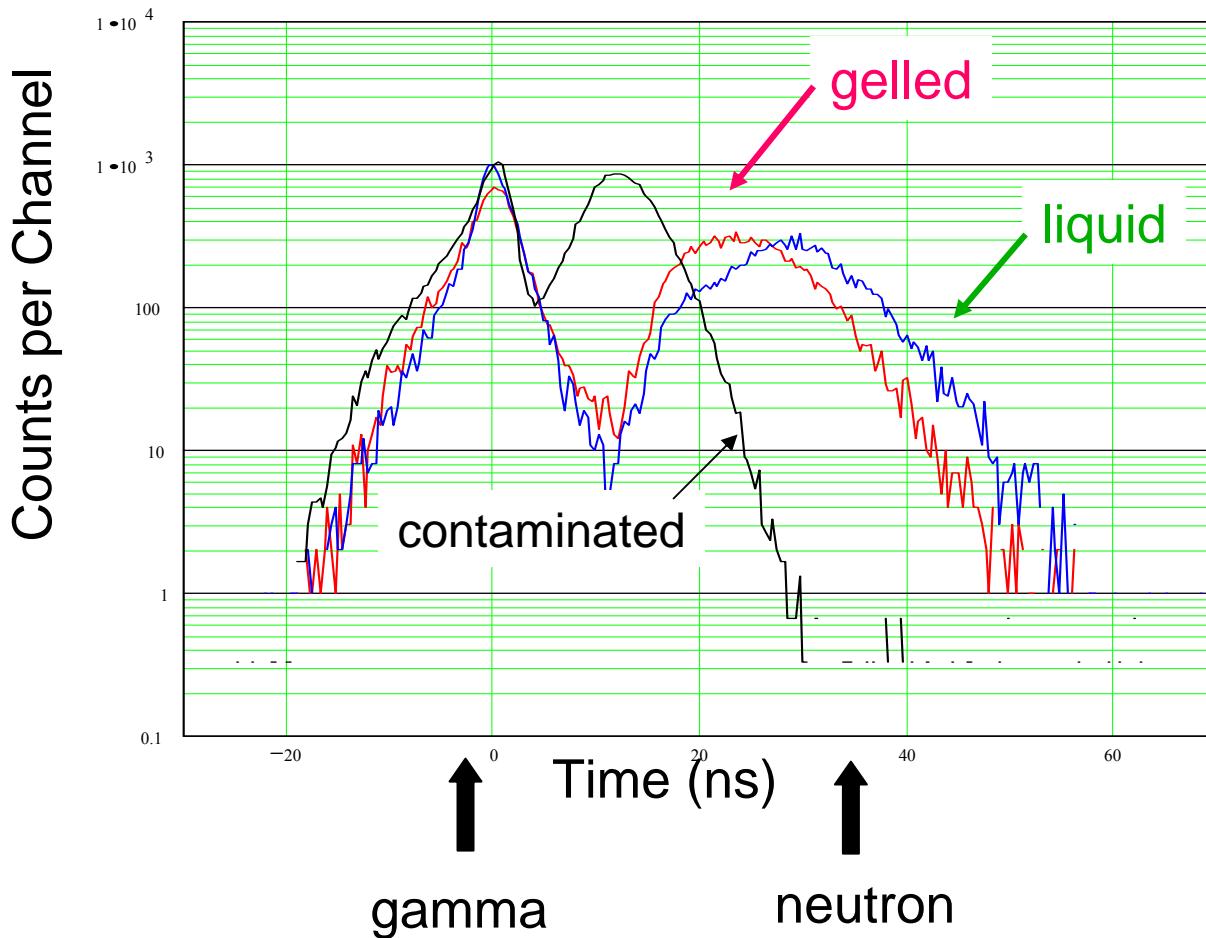
- Self-contained experiment with minimal human involvement
- Scintillator is considered a hazardous payload by NASA
- Significant temperature variations
- Weight and power limitations
- Physical size limitation
- Data to be retrieved and examined after mission is completed

**Demands a conservative, reliable and rugged design**



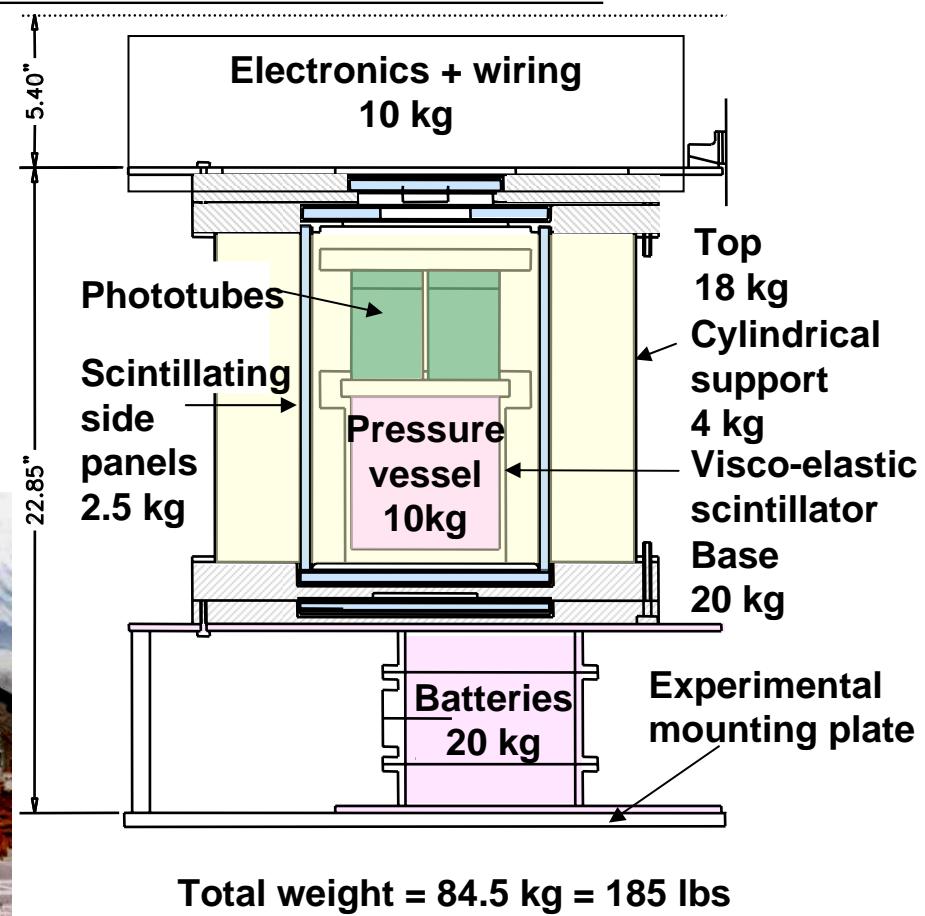
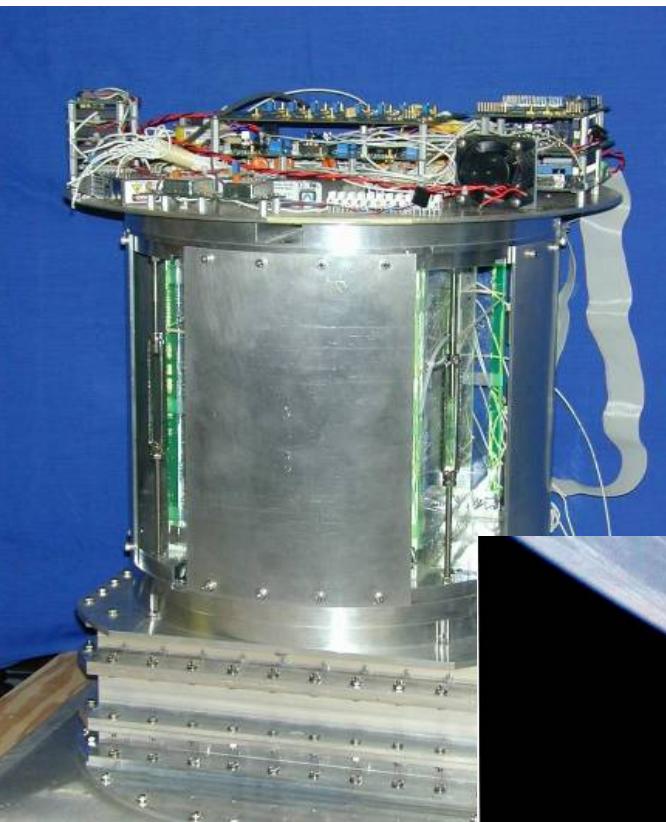
# Performance of Gelled Xylene Scintillator

## Neutron – Gamma Discrimination





# CHENSS Design





# CHENSS Calibration at PTB



# CHENSS Calibration at PTB

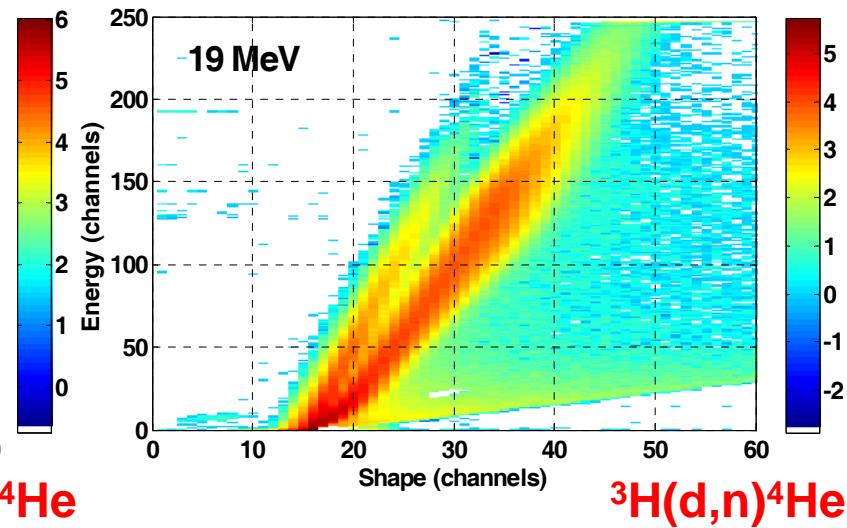
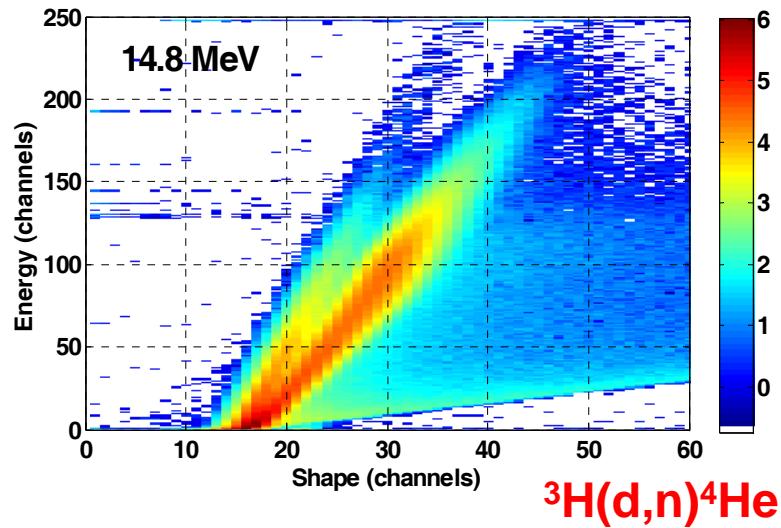
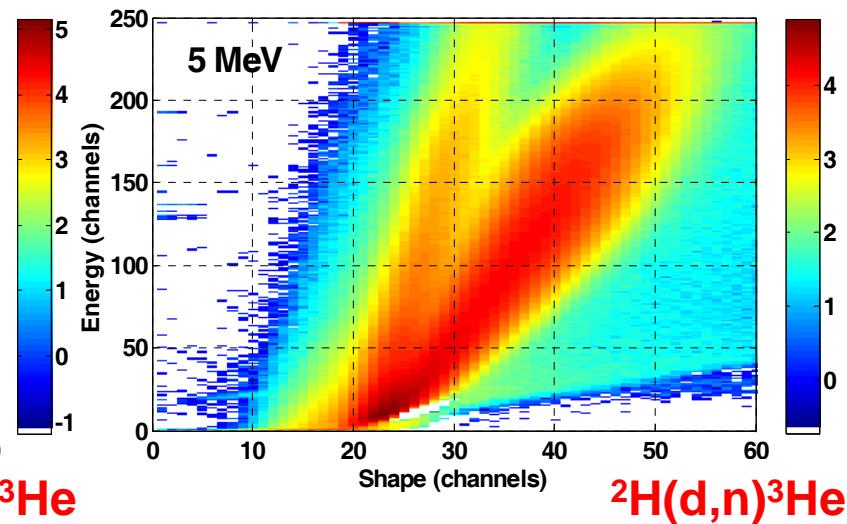
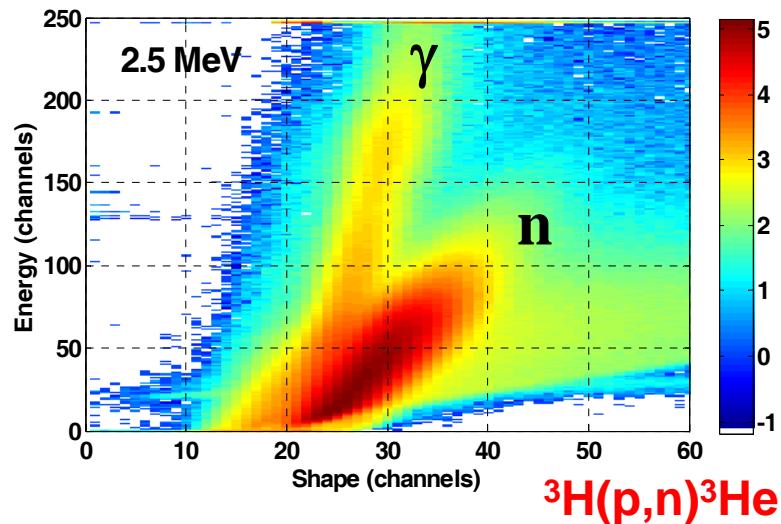
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- CHENSS irradiated by 2.5-, 5-, 14.8- and 19-MeV neutrons
- Shadow-cone and blank-target backgrounds subtracted
- $\gamma$ -ray events removed using pulse-shape analysis
- Spectra unfolded using (5-inch cylindrical) BC-501A response matrix\*
- Fluence compared to independent PTB measurements

\*N. Nakao et. al., Nucl. Instrum. Meth. Phys. Res. Sect. A 362, 454 (1995)

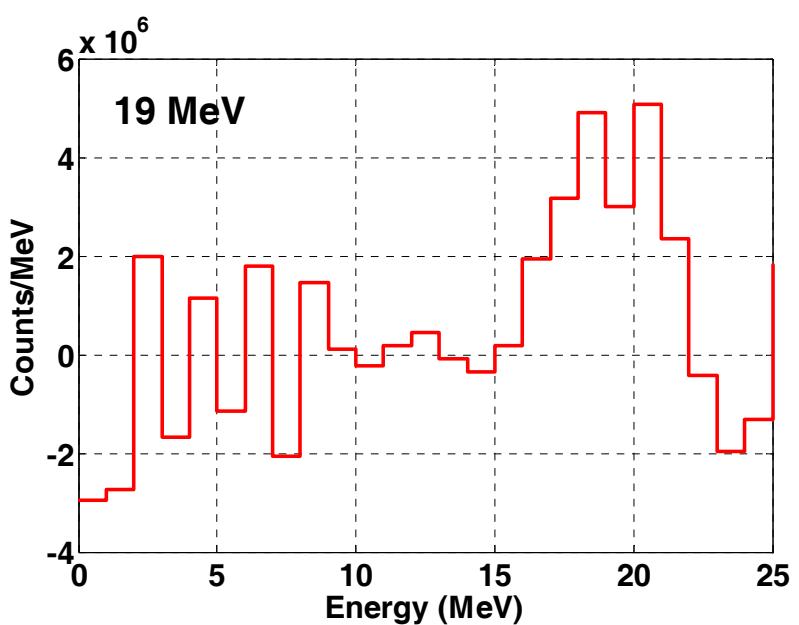
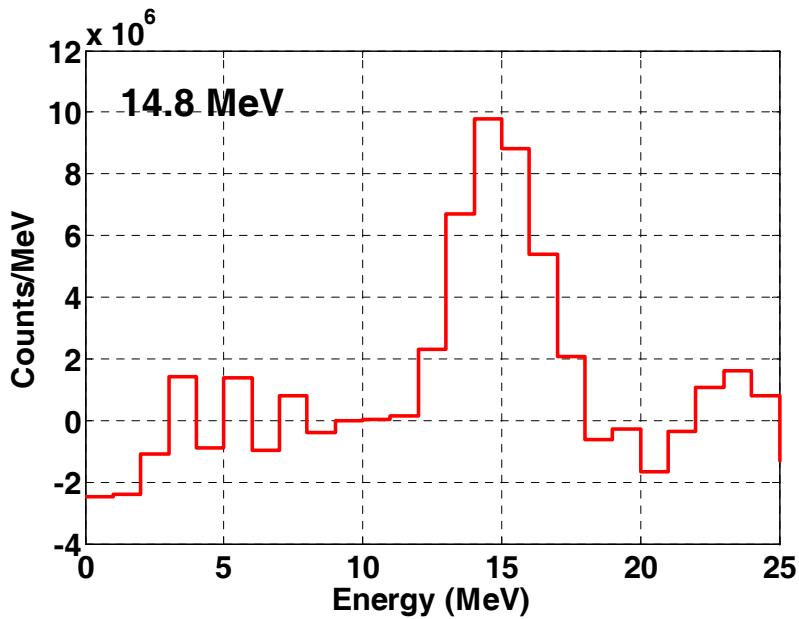


# PTB Irradiation Spectra





# Spectral Unfolding and Fluence Analysis



Neutron energy (MeV)	$\Phi_{\text{PTB}}$ ( $10^5$ neutrons/cm $^2$ )	$\Phi_{\text{CHENSS}}$ ( $10^5$ neutrons/cm $^2$ )
2.5	3.3(3)	2.0(4)
5.0	2.2(2)	1.9(4)
14.8	2.2(3)	2.2(2)
19.0	1.4(2)	1.3(2)

PTB and CHENSS (peak) fluences normalized to CHENSS live-time



# Accelerator Facilities for High-Energy Neutron Calibration



Radiation Protection Dosimetry (2004), Vol. 110, Nos 1-4, pp. 97-102  
doi:10.1093/rpd/nch195

## QUASI-MONOENERGETIC NEUTRON REFERENCE FIELDS IN THE ENERGY RANGE FROM THERMAL TO 200 MeV

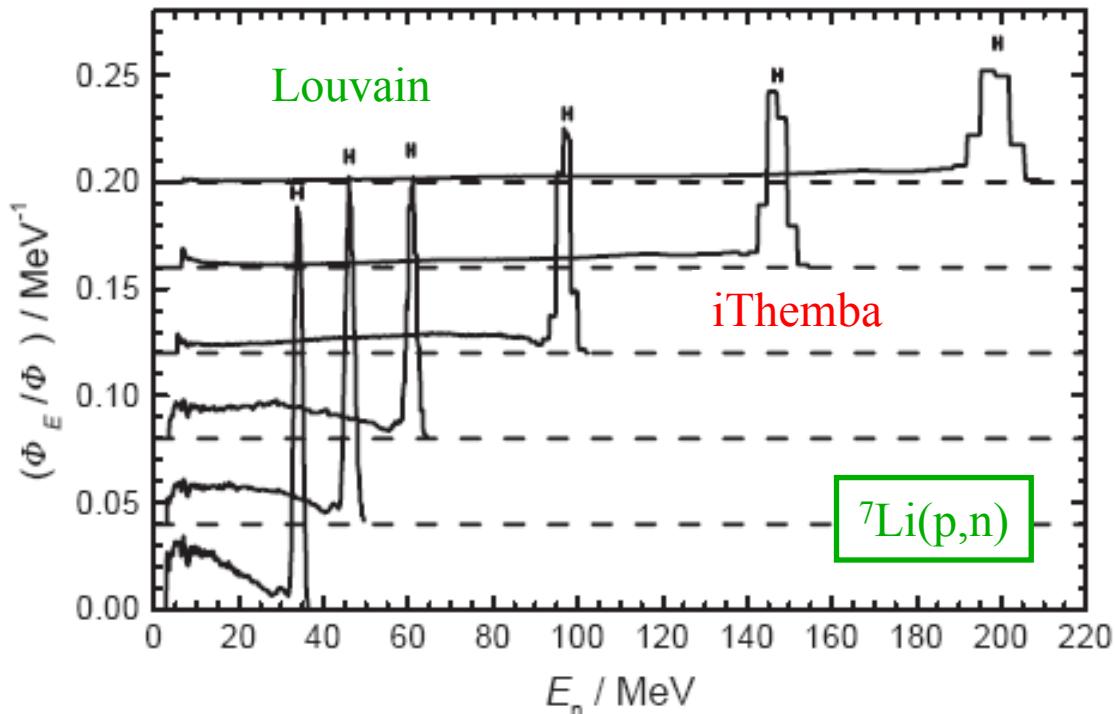
R. Nolte<sup>1,\*</sup>, M. S. Allie<sup>2</sup>, R. Böttger<sup>1</sup>, F. D. Brooks<sup>2</sup>, A. Buffler<sup>2</sup>, V. Dangendorf<sup>1</sup>, H. Friedrich<sup>1</sup>, S. Guldbakke<sup>1</sup>, H. Klein<sup>1</sup>, J. P. Meulders<sup>3</sup>, D. Schlegel<sup>1</sup>, H. Schuhmacher<sup>1</sup> and F. D. Smit<sup>4</sup>

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- PTB neutron beams up to 19 MeV
- Higher energy beams at Louvain-la-Neuve, Belgium and iThemba, South Africa

# Further Measurements for CHENSS

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- If possible, higher-energy (30 – 100 MeV) tests at Louvain-la-Neuve and iThemba (2006 +)
  - Airborne measurements at RMC, Kingston
  - Space mission(s) in the future





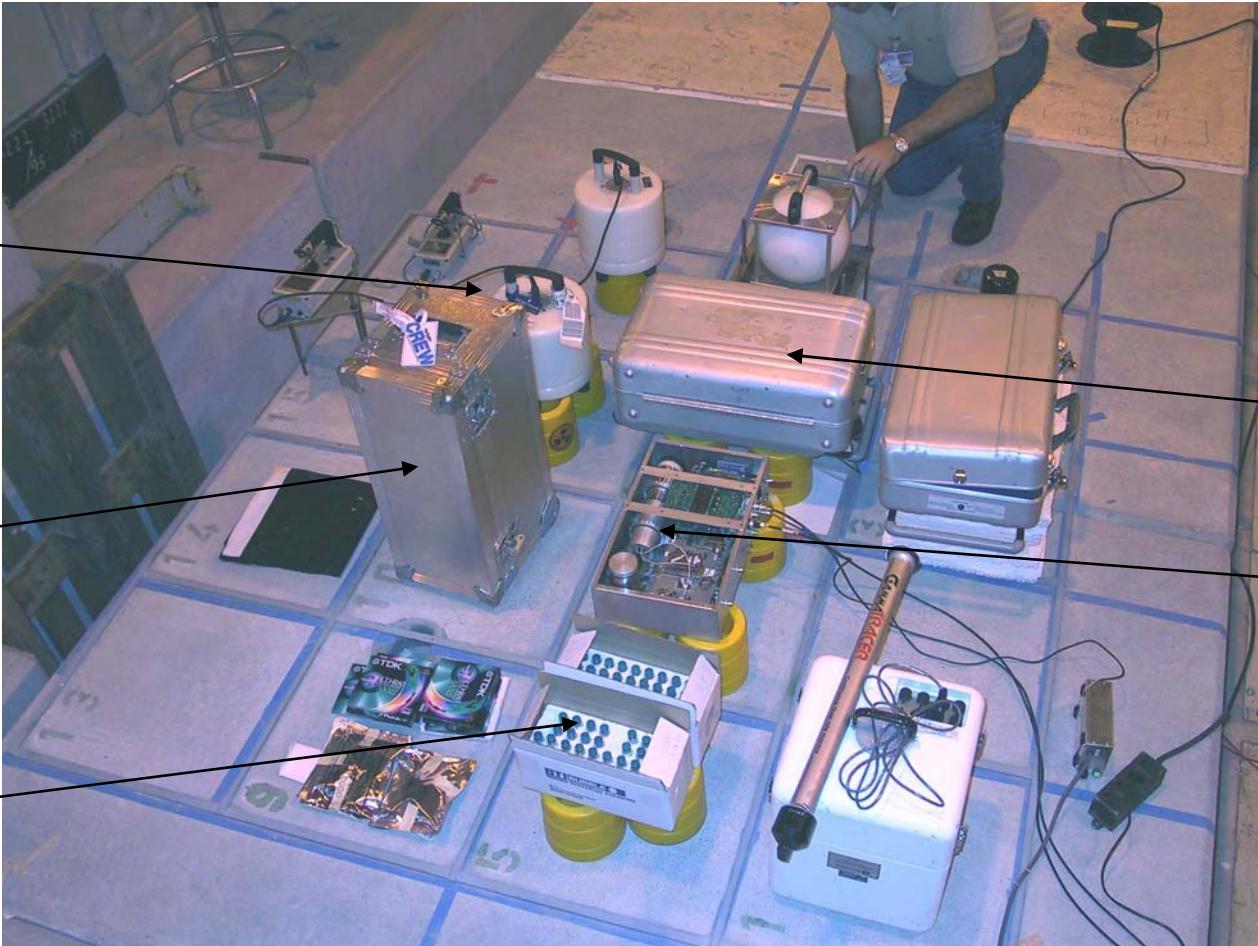
# Neutron Bubble Technology: Ground-Based Calibration at CERF

SWENDI

Ionization  
Chamber

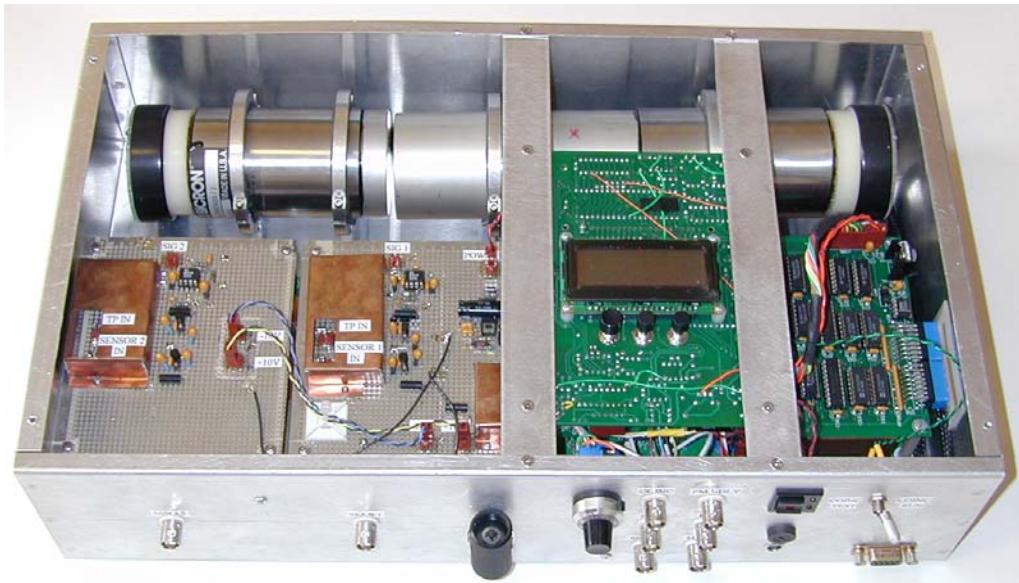
Bubble  
Detectors

TEPC  
NFSE





# Nuclear Fragmentation Separation Experiment



- Charged particle signature accompanies  $\sim 10\%$  of events registered in BD
  - Agreement with FLUKA: charged hadron ( $p, \pi$ ) fluence rate one order of magnitude less than neutrons
- BD-PND ( $260 \pm 50$  pSv/PIC) vs CERF reference value ( $265 \pm 5$  pSv/PIC)



# Mixed-Field Measurement: Aircrew Radiation Studies

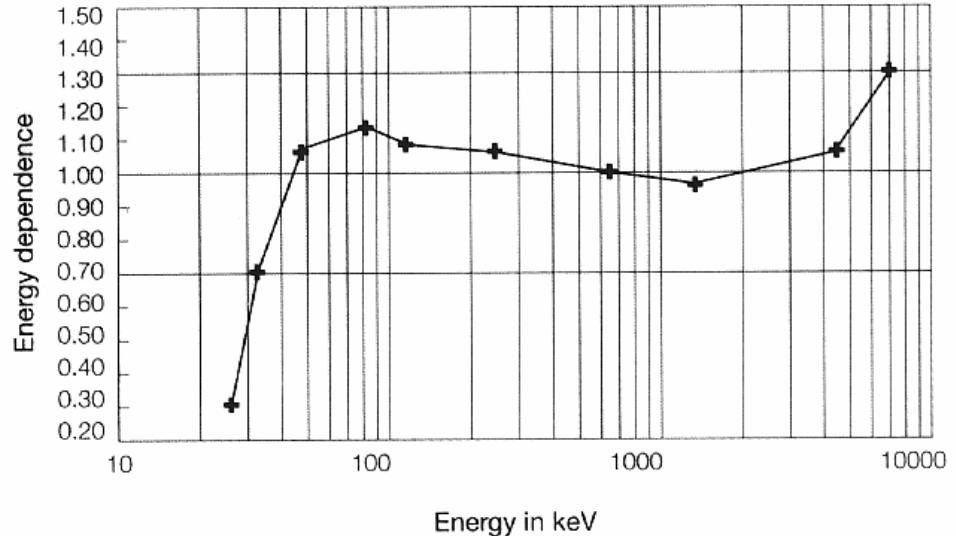


- ~>200 Flights (Portable Instruments)
  - Ionization Counter/ $\text{Al}_2\text{O}_3$  TLDs (low-LET)
  - SWENDI Remmeter/Bubble Detectors (high-LET)
  - Liulin-4N & 4SN (Si-based) LET Spectrometers
  - 2 Tissue Equivalent Proportional Counters (TEPC)

# Ionization Chamber (IC)

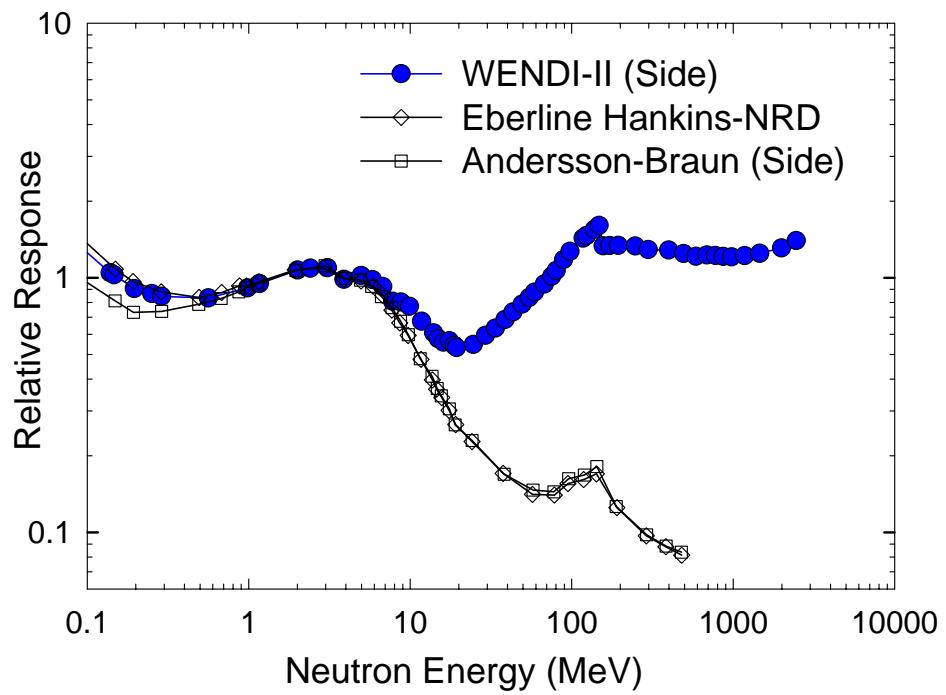
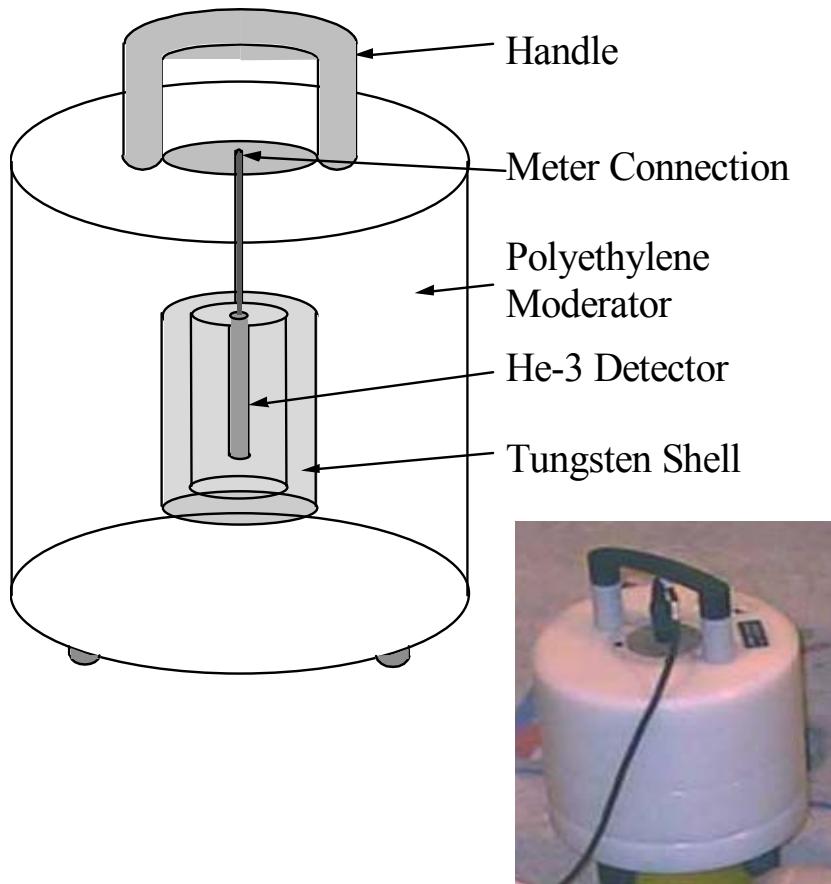


Energy dependence FHT 191 N



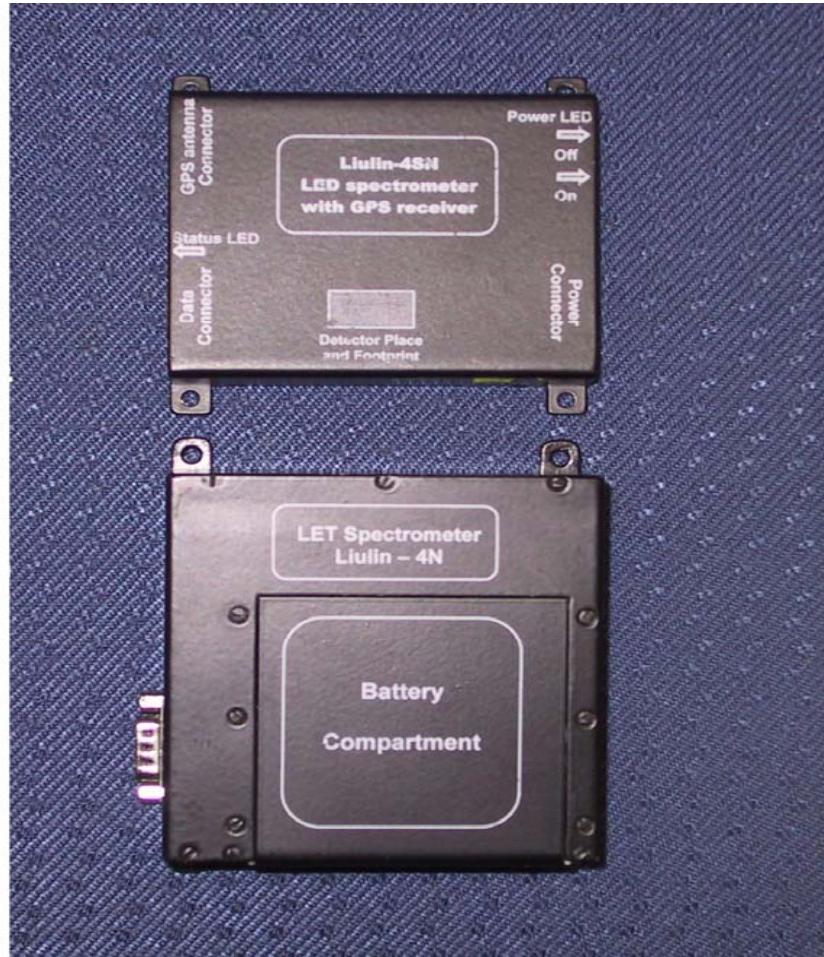


# Extended Range Neutron Detector (SWENDI)



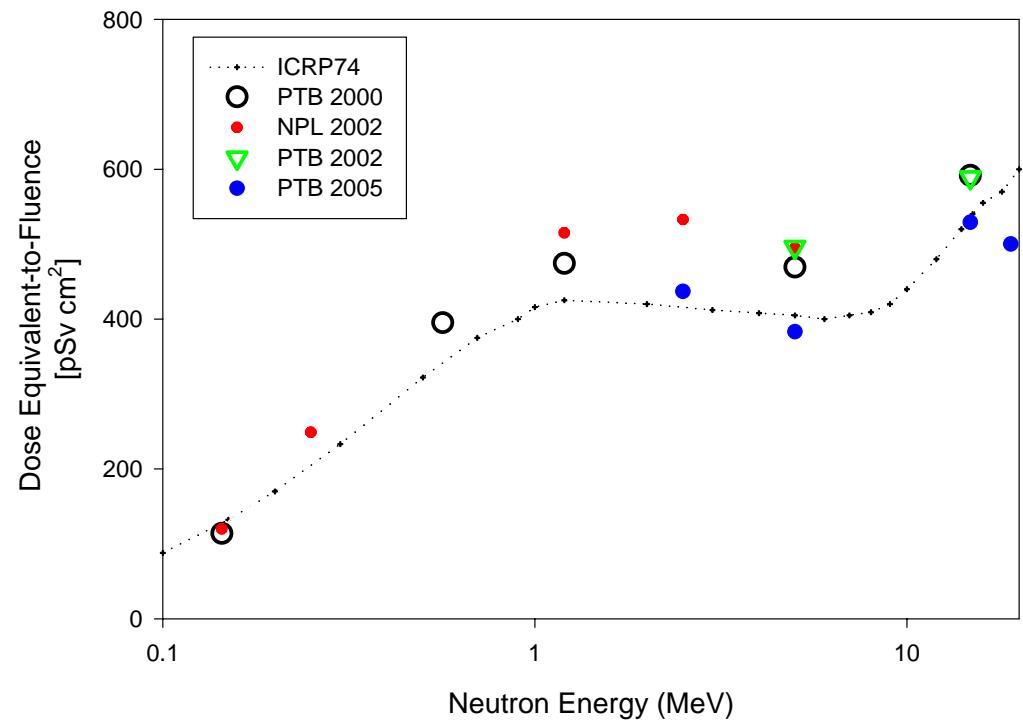


# LIULIN-4N and 4SN (GPS) LET Spectrometer





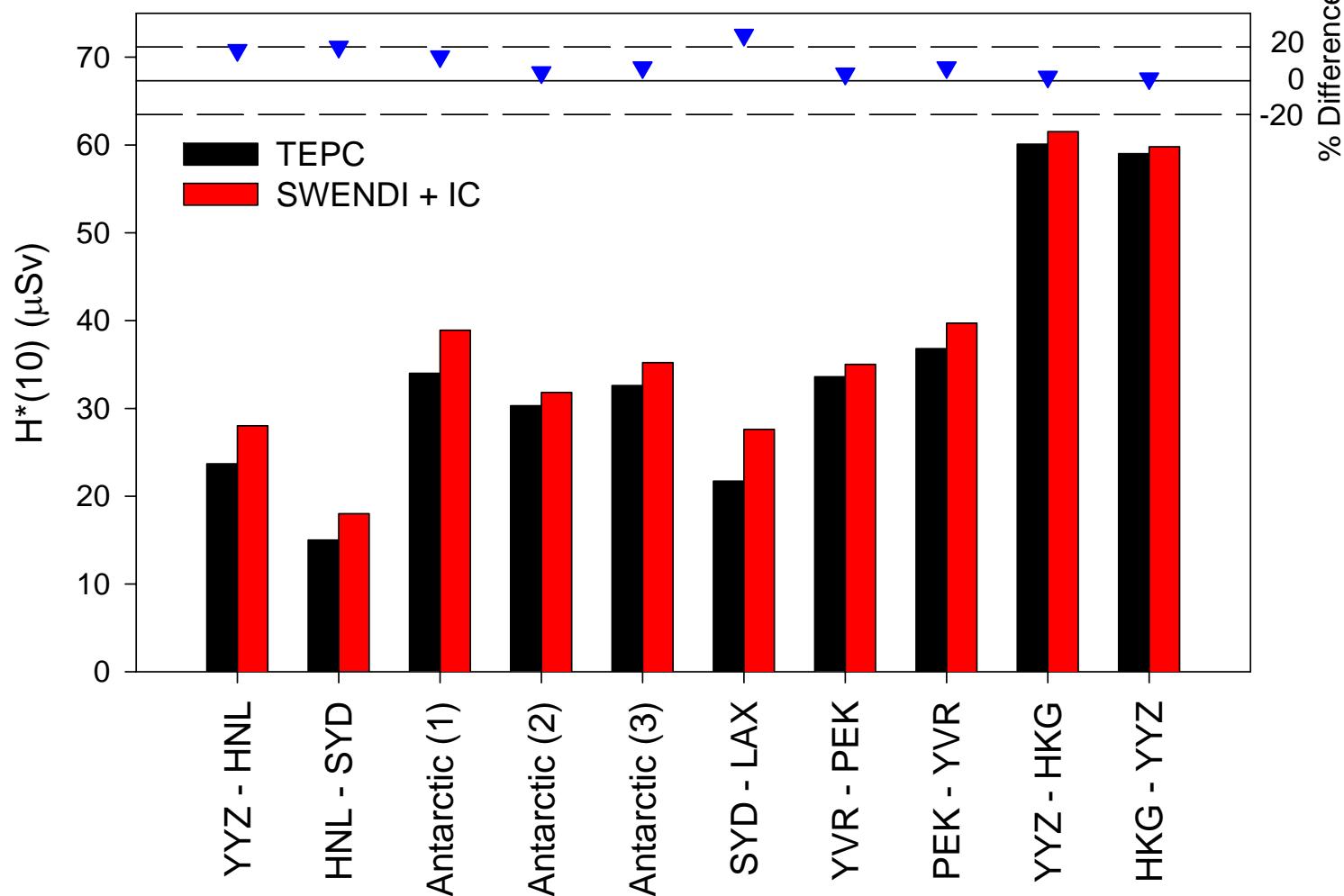
# Tissue Equivalent Proportional Counter



**BDs & TLD's (under foam)**

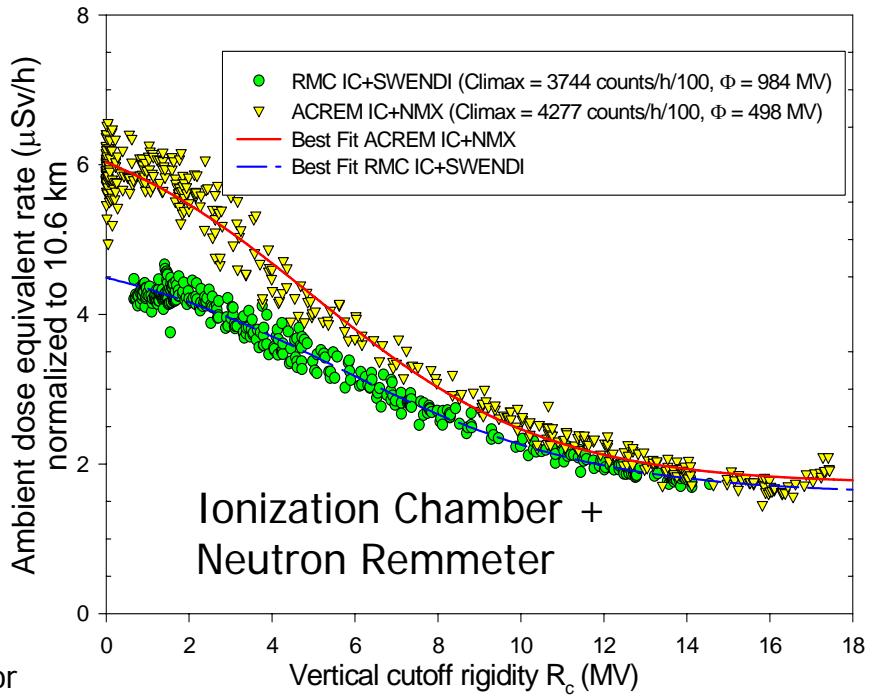
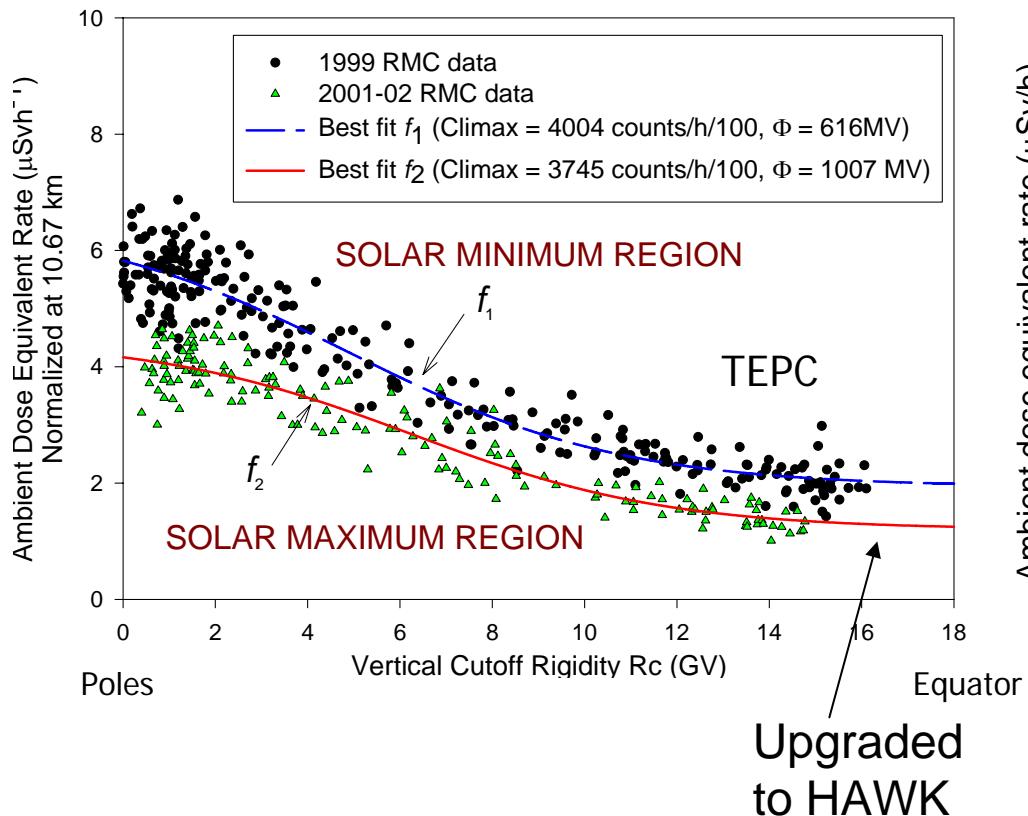


# TEPC & IC + SWENDI: Pacific Routes



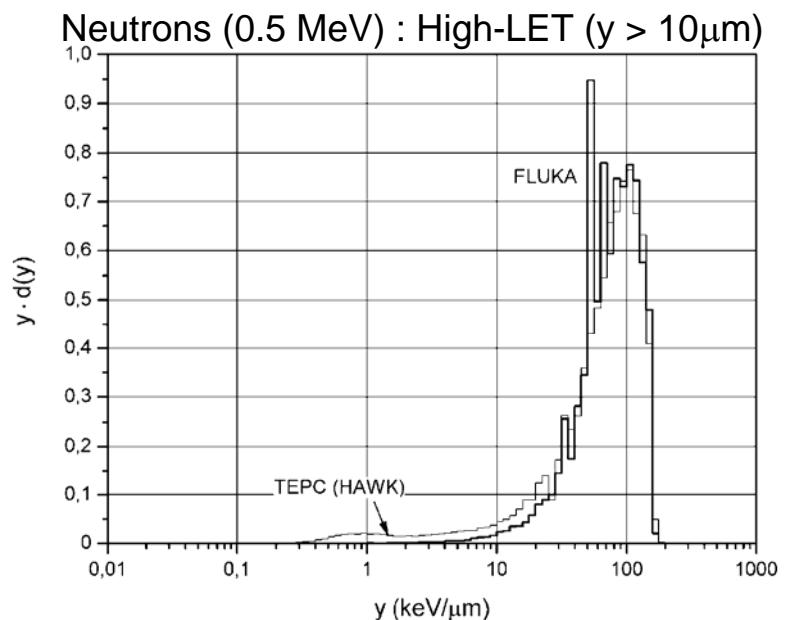
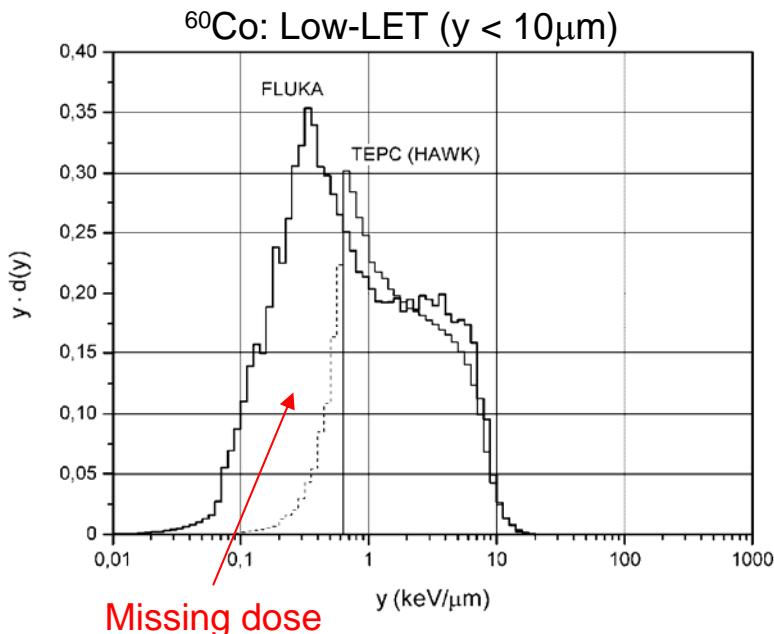


# TEPC & IC + SWENDI World-wide Dose Rate at 10.7 km





# TEPC Limitations for Low-LET Analysis (in Mixed-Field)

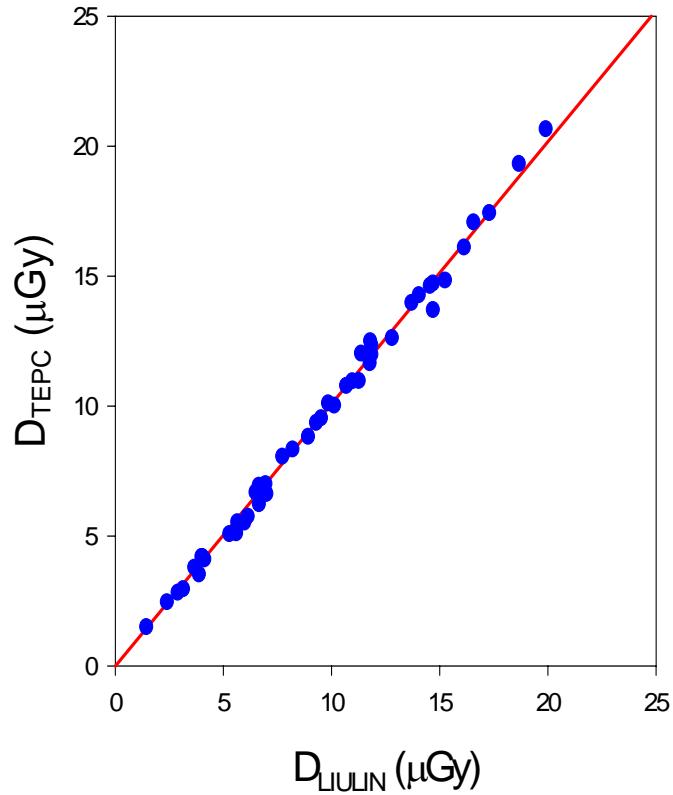
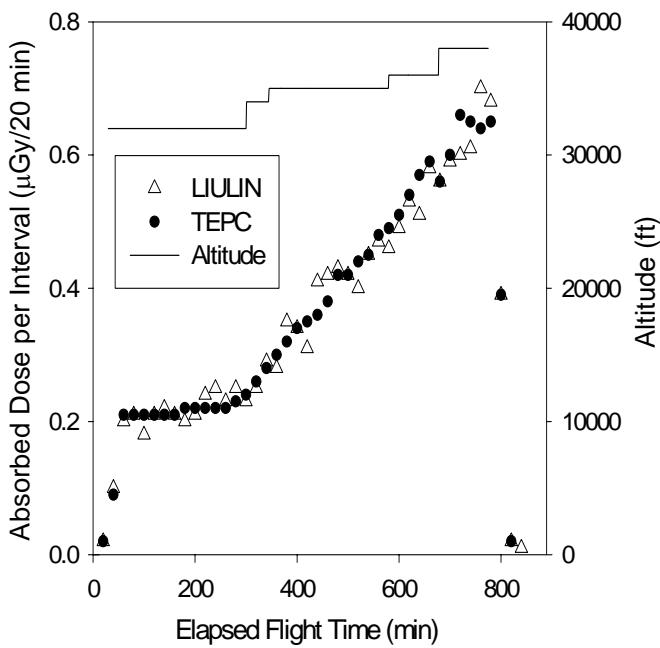


- TEPC unable to provide measurement below  $\sim 0.6 \text{ keV}/\mu\text{m}$  due to electronic noise (S. Rollet et al., Rad. Prot. Dos 110 (2004) 833).
  - Fluka simulation to determine missing low-LET dose
  - Correction applied by manufacturer ( $^{60}\text{Co}$  calibration)



# LIULIN-4N Detector

- Portable instrument needed (periodic checking of PCAIRE code)
- Absorbed route dose (46 flights)
  - LIULIN vs TEPC (Reference Instrument)





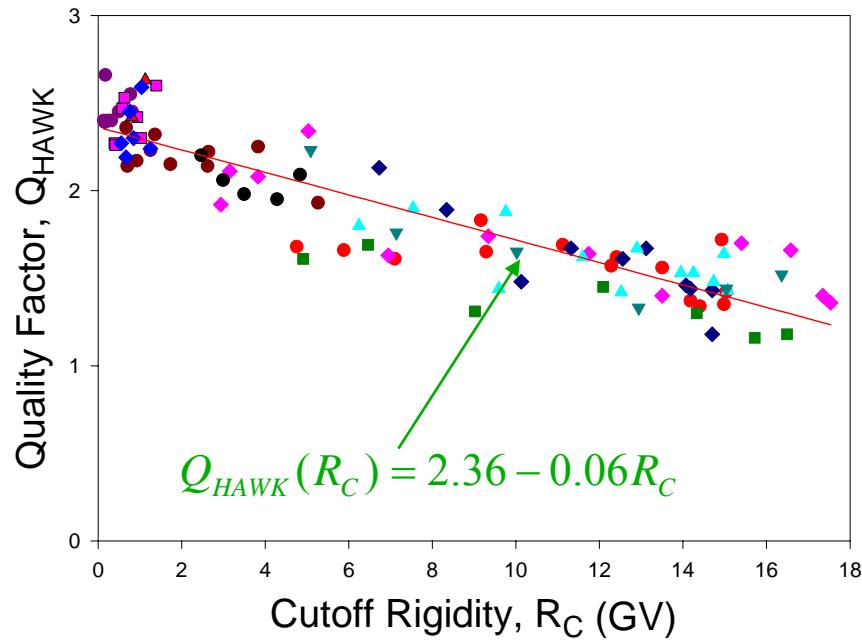
# H\*(10) Analysis for Liulin

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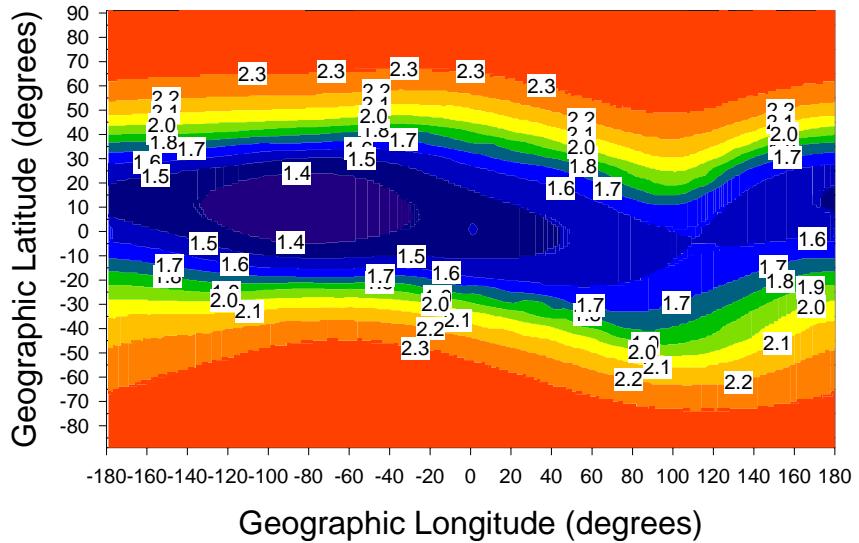
- Methodology (H=QD):
  - (i) Q as a function of cutoff rigidity
  - (ii) LIULIN LET spectral analysis (ICRP-60 Q(L))



# Quality Factor vs Cutoff Rigidity



- 03 Nov 03
- 11 Nov 03
- ◆ 21 Nov 03
- ◆ 02 Dec 03
- ▲ 09 Jan 04
- 31 Oct 03
- 01 Dec 03
- ▼ 08 Dec 03
- 01 Oct 03
- 22 Sep 03
- ▲ 29 Sep 03
- ◆ 04 Oct 03
- Linear Reg'n





# LIULIN Spectral Analysis (ICRP-60 Q(LET))

$$D_i(\mu Gy) = 9.33 \times 10^{-5} \cdot i \cdot n(i)$$

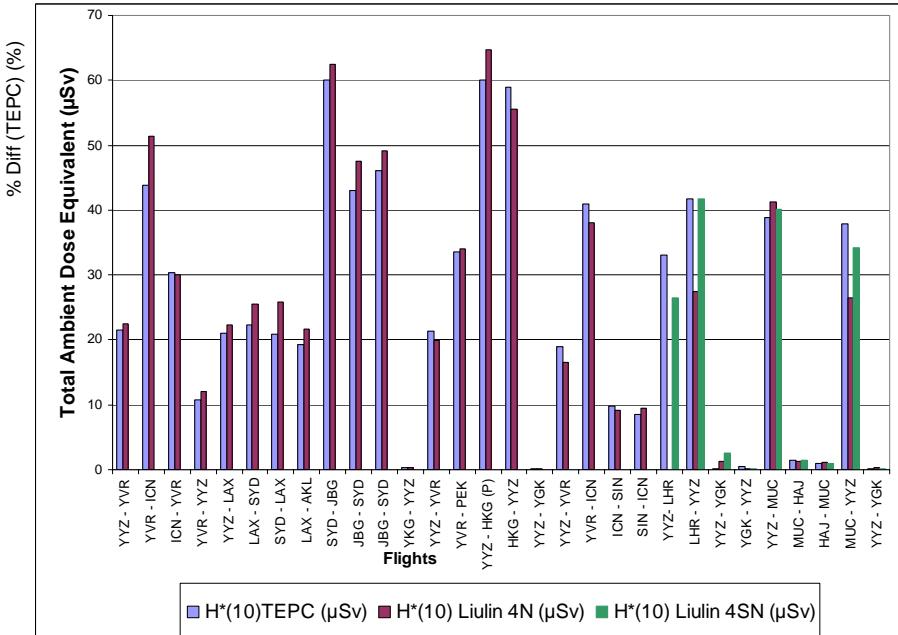
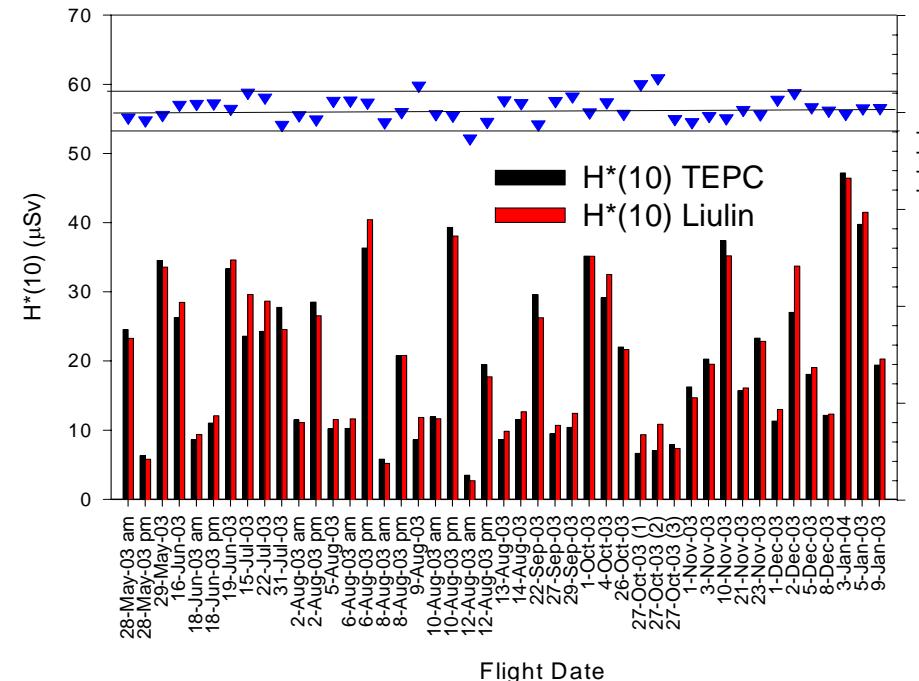
$$\Delta L_i = 0.5 \text{ keV}/\mu\text{m}$$

$$H^*(10)(\mu Sv) = \sum_{i=0}^{255} Q(L_i) D_i$$

Channel I	LET (keV/um)	Counts n(i)	in(i)	Quality Factor (ICRP60) QL	H*(10) (uSv)
0	0.25	0	0	1.000	0.00
1	0.75	5643	5643	1.000	1.58
2	1.25	7642	15284	1.000	4.28
3	1.75	4190	12570	1.000	3.52
4	2.25	2816	11264	1.000	3.15
5	2.75	1657	8285	1.000	2.32
6	3.25	1200	7200	1.000	2.01
7	3.75	842	5894	1.000	1.65
18	9.25	68	1224	1.000	0.34
19	9.75	43	817	1.000	0.23
20	10.25	44	880	1.000	0.25
21	10.75	48	1008	1.080	0.30
22	11.25	30	660	1.240	0.23
23	11.75	30	690	1.400	0.27
196	98.25	0	0	29.080	0.00
197	98.75	0	0	29.240	0.00
198	99.25	0	0	29.400	0.00
199	99.75	0	0	29.560	0.00
200	100.25	0	0	29.963	0.00
201	100.75	0	0	29.888	0.00
202	101.25	0	0	29.814	0.00
203	101.75	0	0	29.741	0.00
253	126.75	0	0	26.647	0.00
254	127.25	0	0	26.595	0.00
255	127.75	0	0	26.542	0.00
Count Sum		27061	116243	24.50	



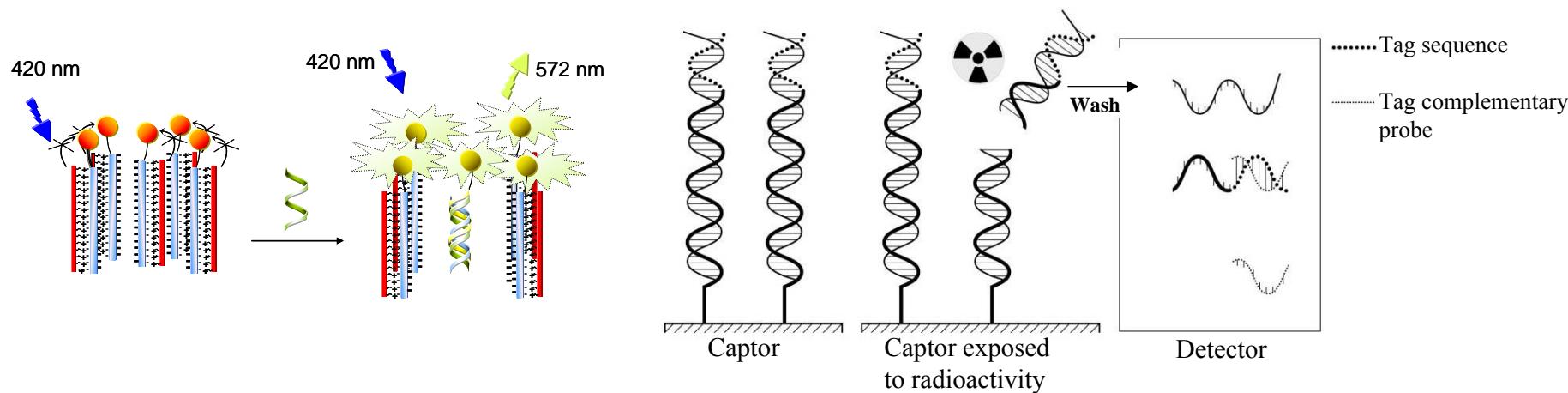
# H\*(10) with LIULIN vs TEPC





# Novel New Technology: DNA Dosimeter

- Polymeric biosensor to detect double strand DNA (dsDNA) breaks induced by radiation (biologically-relevant dosimeter for mixed-field measurement)
  - Captor (nanotechnology) of known amounts of target dsDNA (predefined length with specific terminal sequence tag)
  - Detector (optically-clear hybridization chamber) to read fluorescent signal of cleaved-target dsDNA
  - Correlated against biological dosimetry and compared to physical dosimetry for mixed fields



# Conclusions

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- CHENSS can be used for high-energy neutron spectral measurement
  - Currently being calibrated at accelerator facilities
- NFSE shows promise for n measurement with bubble technology in mixed-field
- Mixed-field measurements made at jet altitudes
  - Good comparison of  $H^*(10)$  by summing low (IC) and high (SWENDI) LET components with TEPC measurement
  - Good comparison of  $H^*(10)$  between TEPC and LIULIN
- Novel technology: biologically-relevant “DNA” dosimeter



# Acknowledgements

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- Funding support from the Life and Physical Sciences Directorate of the Canadian Space Agency (CSA) and Transport Canada
- R. Nolte and S. Rottger of the Physikalisch Technische Bundesanstalt (PTB)
- Thanks are also due to: H.R. Andrews, E.T.H. Clifford, V.T. Koslowsky and R. Noultiy (BTI), M. Boudreau (RMC), C. Vachon (NRC) and L. Tomi (CSA)



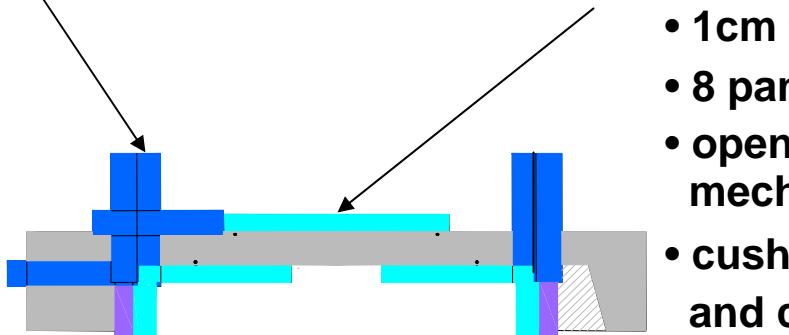
# Cosmic-Ray Detector

(anti-coincident shield, 100% efficient)

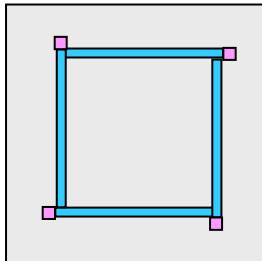


## Phototubes

- one per panel
- cement to plastic
- withstand 20g



Cross-sectional A-A



A —————— A

## Plastic scintillating panel

- 1cm thick, creates strong signal
- 8 panels provide full coverage
- openings for cables and mechanical fasteners
- cushioned with VITON gaskets and caulking from metal surfaces
- no fasteners or tapped holes (no dead areas)